MOBILITY OF WELL-DRILLING ADDITIVES IN THE GROUND-WATER SYSTEM

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Abstract

Components of the drilling fluid may enter an aquifer through any of the avenues available to surface water, such as the outcrop, stream runoff, percolation, and abandoned wells. From the well bore, materials may enter ground water as a consequence of lost circulation, seepage, filtration, or blowout. The contaminating material may be gas, liquid, or solid, and in the form of coarse to fine solids, colloidal suspensions, or solutions. The subsequent behavior and characteristics of the entering substance are determined not only by its initial properties but also, to a large extent, by the properties of the reservoir rock and the interstitial water. Physical separation of suspended solids depends on particle size, shape, concentration, and density and on the pore geometry of the aquifer. The chemical composition and the microorganisms present in the ground water may cause precipitation and decomposition reactions. Adsorption on surfaces and other interfacial phenomena in the reservoir are particularly important and are of a complexity seldom, if ever, met in the laboratory. Movement of drilling fluid materials into the aquifer will be governed by the geohydrologic conditions present. Flow conditions are controlled by the aquifer permeability and the pressure gradient. Such flow may be modified by the introduced substances and their effect on existing conditions in the aquifer.

INTRODUCTION

The purpose of this paper is to examine the factors involved in the movement of drilling-fluid components in the ground-water reservoir. Components of the drilling fluids will be considered generally and no attempt

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will be made to deal with specific substances. Examples of the important mechanisms involved in the movement of liquids, solids, and gases from the borehole into the formation will be discussed.

Some definitions may aid in delineating the scope of this review. An "aquifer" is a geologic "formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs" (ref. 36). A "drilling fluid" is a material used as an aid to tools in the excavation of earth. Accordingly, the drilling fluid may be employed with such varied tools as augers for foundation borings, and cable tool and rotary drills for ground water and petroleum exploration and for mineral exploration and mine development. Composition of the drilling fluid may range from dry air or potable water to diesel oil containing gellants, emulsifiers, and several types of suspended solids. A "contaminant" is any introduced substance, or product of an introduced substance, that modifies the properties of the initial ground water to such an extent that its usefulness in the desired application is impaired.

This discussion is concerned with the movement of any substance that enters the ground-water reservoir as a consequence of the drilling operation, whether such a substance is a drilling-fluid additive, or fluids or earth materials derived from the excavation.

The term "drilling fluid" embraces an extremely variable composition of matter. Characterized according to the principal component as "gas," "water," or "oil," usually two (somethimes all three) fluids are present, along with suspended and dissolved materials. If the major component is a liquid, the drilling fluid is called "mud" and is broadly classed as "water mud" or "oil mud." Prior publications (refs. 2, 22, and 23) and other papers presented at this conference deal with the components of drilling fluids in some detail and they need not be reviewed here.

CONTAMINATION FROM THE SURFACE

Contamination of ground water from the surface may originate in earthen pits in which mud is placed, either for circulation or storage; from leaching of cuttings; from spilled mud or ingredients; from containers for the additives, and from mud and materials discarded on completion of drilling operations.

In drilling deep wells, practically without exception the mud is contained in steel tanks. The cost of the mud, as well as possible reuse or sale of excess mud, justifies adequate facilities for storage. Many small rigs also use steel tanks for the mud being circulated, although surplus mud is stored in earthen pits or discarded on the surface (figure 1). When earthen pits are used in the active mud system, if the surface exposed in the dug pit is not clay, the surface is sealed with bentonite or other clay before mud mixing is begun (figure 2).

Bulk handling of the principal mud constituents has greatly reduced spillage and waste of materials. More attention should be given, however, to the handling of water-soluble additives. Not infrequently the contents of opened bags containing caustic soda, lignosulfonates, or the like, will become caked and will be discarded, thus becoming a potential source of ground-water contamination under certain geologic conditions. "Good housekeeping," therefore, is a highly desirable practice.

The cuttings separated at the surface and the adhering drilling fluid are regarded as waste products. A considerable quantity of earth is excavated during the drilling operation. For example, in drilling a municipal water well in Houston, Texas, to a depth of 2,500 ft., over 14,000 cubic feet of earth weighing over 1-1/2 million pounds must be brought to the surface. Usually cuttings are not regarded as a source of ground-water contamination, with the exception of soluble salts, such as halite or gypsum. Disposal of cuttings and mud in some locations is an expensive item in well drilling. In the Los Angeles basin, for example, cuttings and excess mud must be hauled to designated sumps for disposal. In The Netherlands, the drill site is covered with a concrete apron surrounded by dikes. All waste water, in addition to cuttings and mud, must be removed from the location.

Components of the drilling fluid may enter ground water through any of the routes available to surface water, such as the outcrop of the aquifer, streams, percolation, and abandoned wells. Shallow aquifers are often exposed to contamination through construction borings; excavations for foundations, sumps and mud pits, and by drilling relatively shallow holes for seismic and mineral exploration.

Figure 1. Mud tanks for water-well drilling.

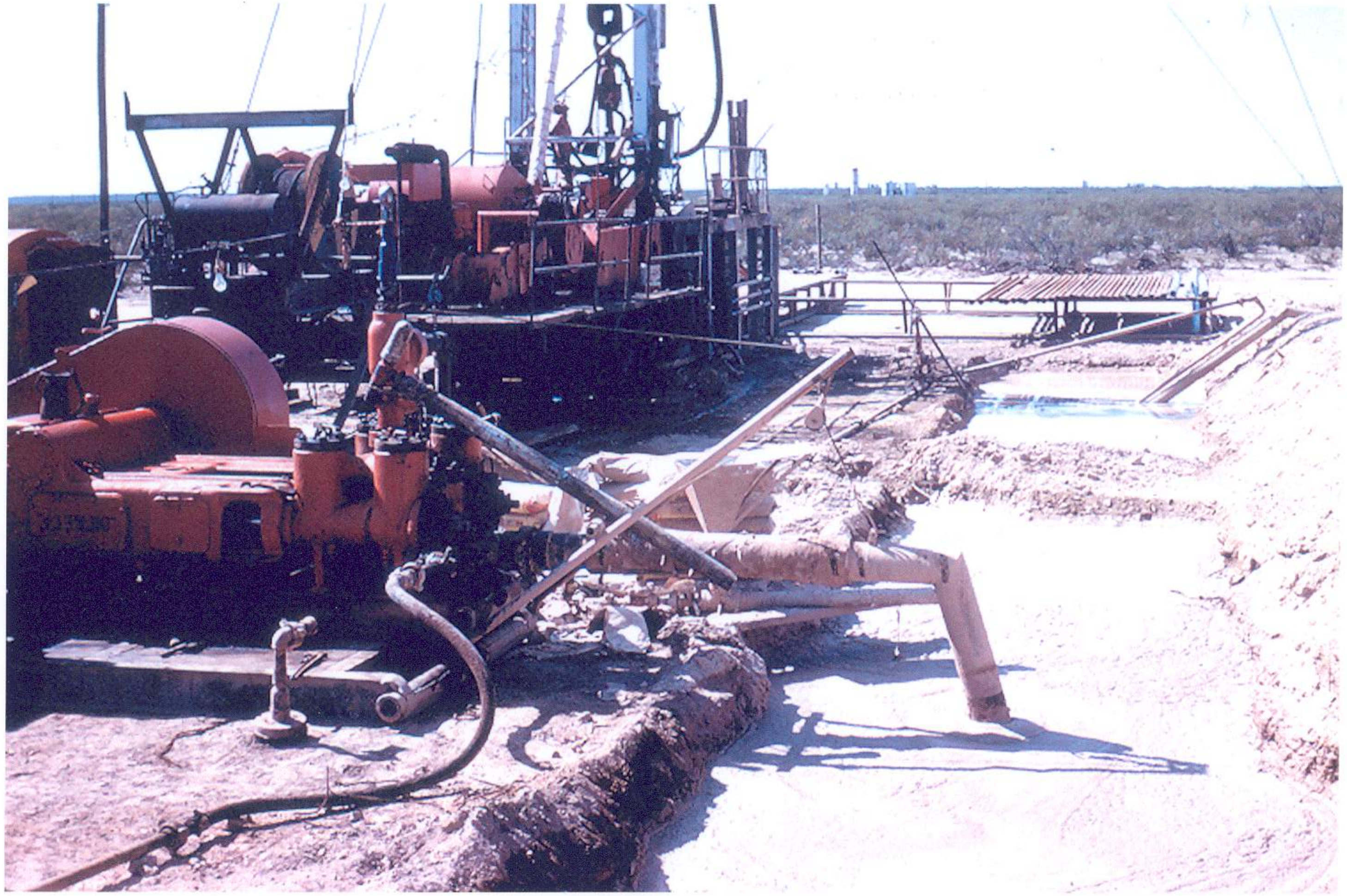
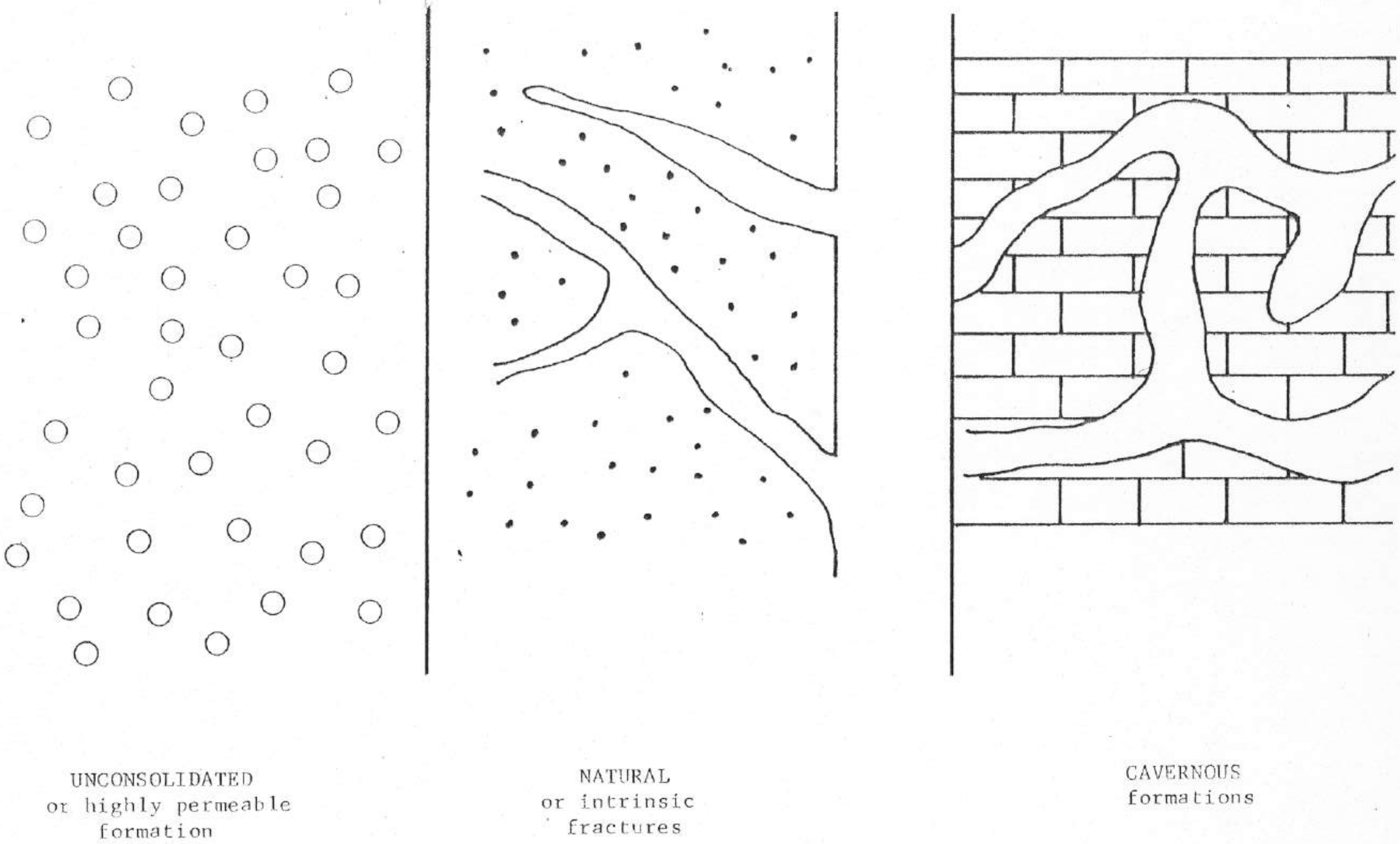


Figure 2. Bentonite-scaled mud pit for oil-well drilling.



(After Messenger - 1968)

Figure 3. Types of formations that can take whole mud.

of what is in fact a component of a drilling-fluid additive was reported by Sweet and Fetrow (ref. 43). A case of ground-water pollution was reported involving wood-waste disposal (i.e., lignin-tannin, which is a common drilling-fluid additive in oil-well drilling operations).

While drilling with water, seepage may occur into porous, permeable formations exposed in the borehole. Finely-divided cuttings carried by the water enter the openings and, as individual pores become bridged by the larger particles, successively smaller particles are filtered out. Clay or other material of colloidal dimensions converts seepage into filtration. The passage of liquid into the formation then becomes dependent on the amount and physical state of the colloidal material in the drilling fluid and not on the permeability of the formation (ref. 10). In porous media, the thickness and cha acter of the filter cake precondition the extent of liquid invasion into the formation during the drilling operation. When circulation is stopped, cake thickness continues to increase but at a decreasing rate (figure 4). Studies of the filtration of oil-field muds have shown the permeability of the filter cakes to be in the range of 10^{-3} to 10^{-5} millidarcys (refs. 5, 11, and 46). Estimations have been made of the rate of invasion of filtrate into sands in the course of drilling (refs. 21 and 47). A radius of invasion of nearly 2 feet was calculated for a period of 138 hours between penetration of a sand and cementing of casing. More than 90 percent of the total filtrate flowed from the mud while it was circulating during about 75 percent of the elapsed time (ref. 21.)

The most spectacular method of introducing contaminants into ground water is by means of a blowout. This uncontrolled entry of fluids into the borehole may force gas into shallow aquifers and cause water wells to begin flowing or even to blow out. Keech (ref. 32) cites a dramatic case history of widespread ground-water contamination by a subsurface natural-gas well blowout in the vicinity of a number of water wells. In another example, the effects of a blowout in the Bammel field north of Houston, Texas, are still evident after 30 years. Water wells drilled several miles from the site of the blowout often require prolonged completion operations because gas coming out of solution in the water interferes with the functioning of the pumps.

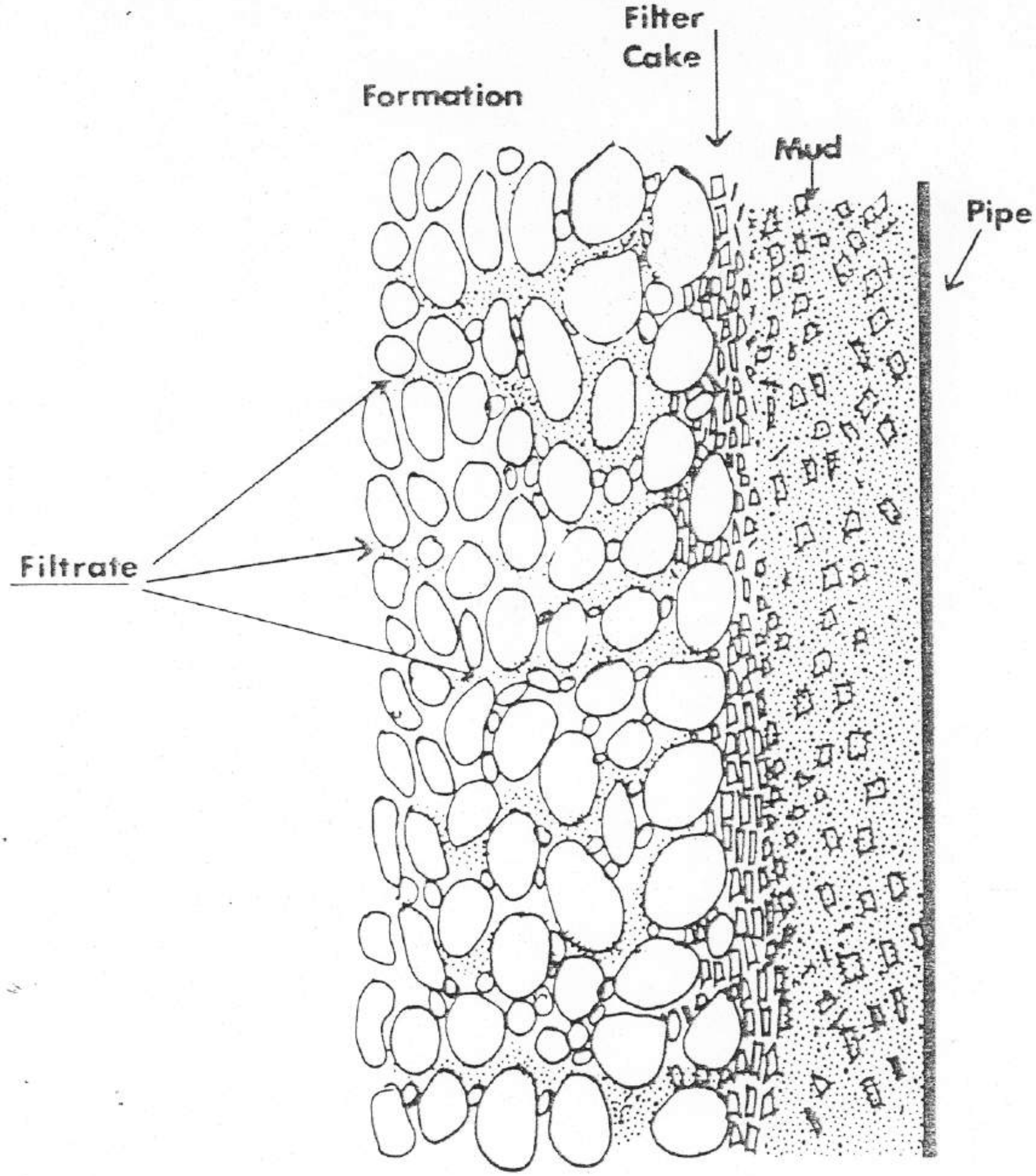


Figure 4. Cross section showing borehole and adjacent formation (note mud-filtrate invasion characteristics).

Contaminants can enter the ground-water reservoir as wells are drilled, during their operational life, or following their abandonment. Possibly of greatest potential consequence is the nearly unavoidable introduction of biological agents into the aquifer via drilling fluids. Subsequently, the growth of certain types of bacteria that cause corrosion and incrustation may be an important factor in contamination of aquifers. The routes by which contaminated water can enter the ground-water reservoir through faulty oil or water well construction have been briefly explored by Collins (ref. 15) and by Campbell and Lehr (ref. 13) and need not be treated here.

IMMOBILIZATION OF SUSPENDED SOLIDS IN THE AQUIFER

As has been shown, contaminating substances from drilling operations may enter ground water from the surface or from the well bore. The material may be gas, liquid, or solid. It may be in the form of coarse to fine solids, colloidal suspensions, or solutions. It may be stable or unstable; reactive or unreactive. The subsequent behavior of the entering substance is determined not only by its properties but also, to a large extent, by the properties of the reservoir rock and the interstitial water.

Except under very unusual conditions, particles that will be retained on 200-mesh sieve--the API designation for sand (ref. 1)--can be expected to be removed near the point of entry into the aquifer. Particles having an effective diameter less than 74 microns (200-mesh) also will be subject to gravitational effects that will decrease in importance as the particles become smaller. Sedimentation is not a significant factor in the separation of particles smaller than one micron (figure 5).

The importance of filtration in industrial processes has led to numerous studies of the mechanism. Herzig, Leclerc, and LeGaff (ref. 26) cite 74 references in their examination of the flow of suspensions through porous media. The authors point out that several mechanisums are involved, namely: (a) the contacting of particles with retention sites, (b) the fixing of particles on sites, and (c) the escape of previously retained particles. Factors involved in the system are: (a) the flow rate, viscosity, and density of the carrier fluid; (b) the concentration, size, and shape of the suspended particles, and (c) the geometry of the porous medium.

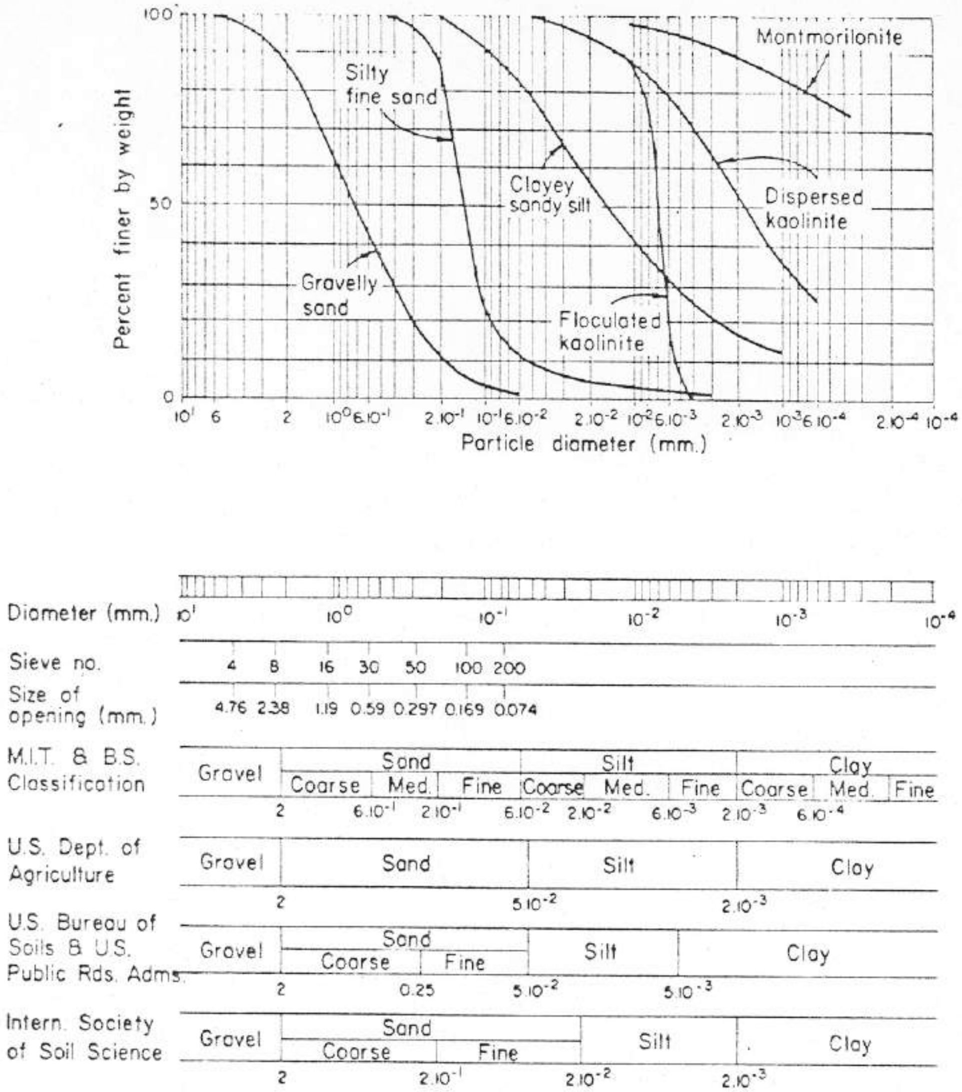


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Figure 5. Typical grain-size distribution curves for various soils with major used classification. (Bear - 1972).

Retention sites can be classed as: (a) surface of a grain making up the bed, (b) crevice between the surface of two grains, (c) constriction and, (d) cavern, or sheltered area formed by several grains (see figure 6a). Forces that hold the particle immobilized include: (a) axial pressure of the liquid, as at a constriction; (b) friction forces, as on a particle wedged in a crevice; (c) surface forces: Van der Waals forces of attraction, and electrostatic or electrokinetic forces which are either attractive or repulsive dependent on the system, and (d) chemical forces, which may involve chemical bonding between the particle and the surface. The process of capture may involve: (a) sedimentation; (b) inertia, i.e., the particles cannot follow the changing path of the liquid; (c) hydrodynamic effects caused by nonuniform shear field and nonsphericity of particles; (d) direct collision with convergent pore walls; and (e) diffusion by Brownian motion into areas not flushed by the suspension (see figure 6b).

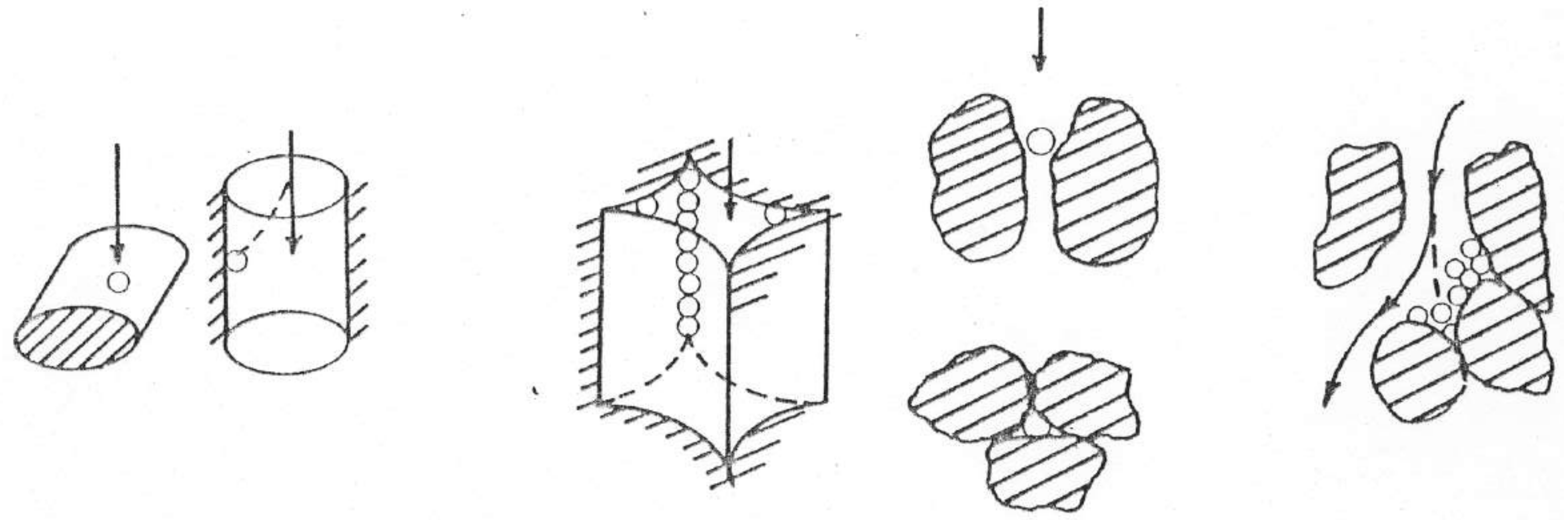
"The flow of suspension through porous media is a very complex phenomenon owing to the diversity of the mechanisms involved" (ref. 26).

MOVEMENT WITHIN THE AQUIFER

Drilling-fluid filtrate invasion in highly permeable sands often appears from electrical logs to be less near the base of the sand than near the top. Doll (ref. 18) concludes that filtrates rise in the sand after passing the filter cake barrier at the hole wall. This, of course, assumes that the filtrate density is less than the denisty of the ground water and suggests that if the density of the ground water is higher than the density of introduced material, the invasion would be strictly gravity controlled. The filtrate would then invade the lower part of the aquifer more rapidly than at the top.

In a study on deep-well waste disposal and waste surveillance, Kazmann (ref. 31) has demonstrated that the density difference between the ground water and the introduced carrier fluid clearly dictates the character of the invasion front with time.

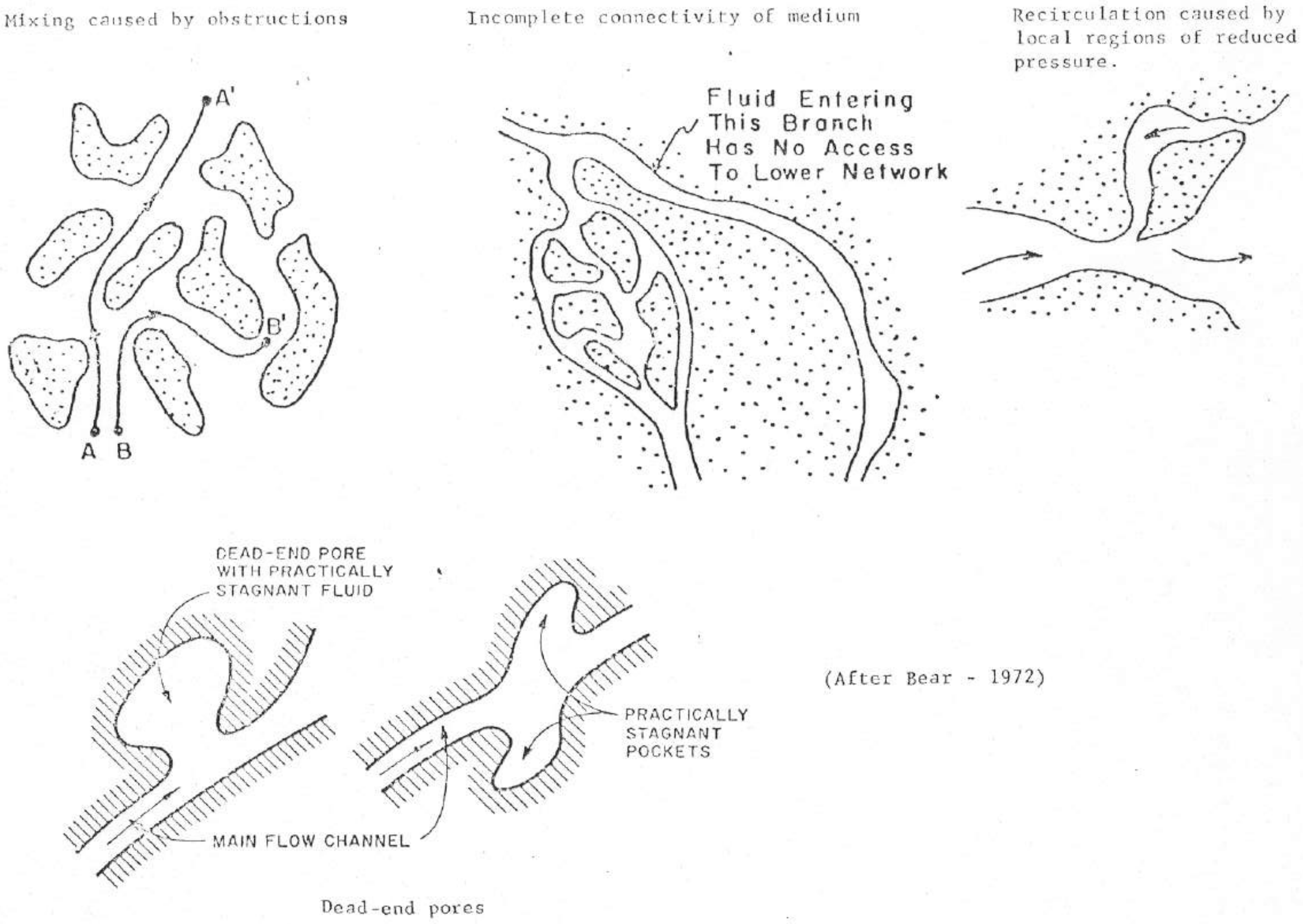
Once fluids and solids pass the filter cake and hole wall into the formation, invasion characteristics of the carrier fluid are affected by many physical, chemical, and biological factors. Numerous macro- and microformational factors affect its path, its rate of flow, and its chemical composition. Information on the course of contaminants in the ground-water system is now voluminous and hence will not be reviewed in detail at this



SURFACE SITES CREVICE SITES CONSTRICTION SITES CAVERN SITES

(After Bear - 1972)

Figure 6a. Classification of retention sites.



Mixing caused by obstructions

Incomplete connectivity of medium

Recirculation caused by local regions of reduced pressure.

Dead-end pores

(After Bear - 1972)

Figure 6b. Typical groundwater flow paths in porous media (micro-range) and cavernous media (micro- to macro-range).

time (ref. 12). However, some of the features pertaining to the potential behavior of drilling fluids within the ground-water system will be explored.

Although open-channel, ground-water flow, e.g., in joints, interconnecting solution channels, fault traces, etc., is not uncommon in the subsurface, porous media flow is emphasized here because of its wide applicability to the major aquifer type--sands, sandstone, etc. The physical aspects of ground-water flow are of fundamental importance to a discussion of mobility of contaminants.

Bond (ref. 6) discusses flow patterns of variable-density ground water and the effects of troughs formed by permeability barriers within aquifers and the effects of structural troughs, saddles, anticlines, and synclines. Childs, et al. (ref. 14) explore the concept of a "waste plume" and suggest that the plume pattern may be complex and may not follow regional ground-water flow, as indicated by other workers (ref. 40). See figure 7.

Ground-water flow through porous media is characterized by laminar flow at low Reynolds numbers (Re), where gradient is held constant. Viscous forces predominate and the Darcy Law is valid. As Re increases, a transition zone is encountered at the lower end; the laminar regime with viscous forces predominating passes to another laminar regime characterized by inertial forces. At the upper end of the transition zone, a gradual passage to turbulent flow is observed. Darcy's Law is not valid in the transition and turbulent zones (ref. 4). Average ground-water flow rates vary widely depending on gradient, permeability, and other geologically-controlled factors.

It is clear that the laminar flow is of predominance in the porous media under consideration here and that it simplifies the effects of the flow regime on the chemical and biological parameters within the aquifer.

Flow paths, when encountering changes in permeability (or changes in ground-water density), will be refracted according to the tangent rule, whereas light is refracted according to the sine rule (ref. 16). See figure 8. This, of course, will affect the chemical and biological parameters to be discussed later. Suffice it here to state, however, that an abrupt change in flow direction may affect one or more characteristics of the carrier fluid, including any introduced contaminant.

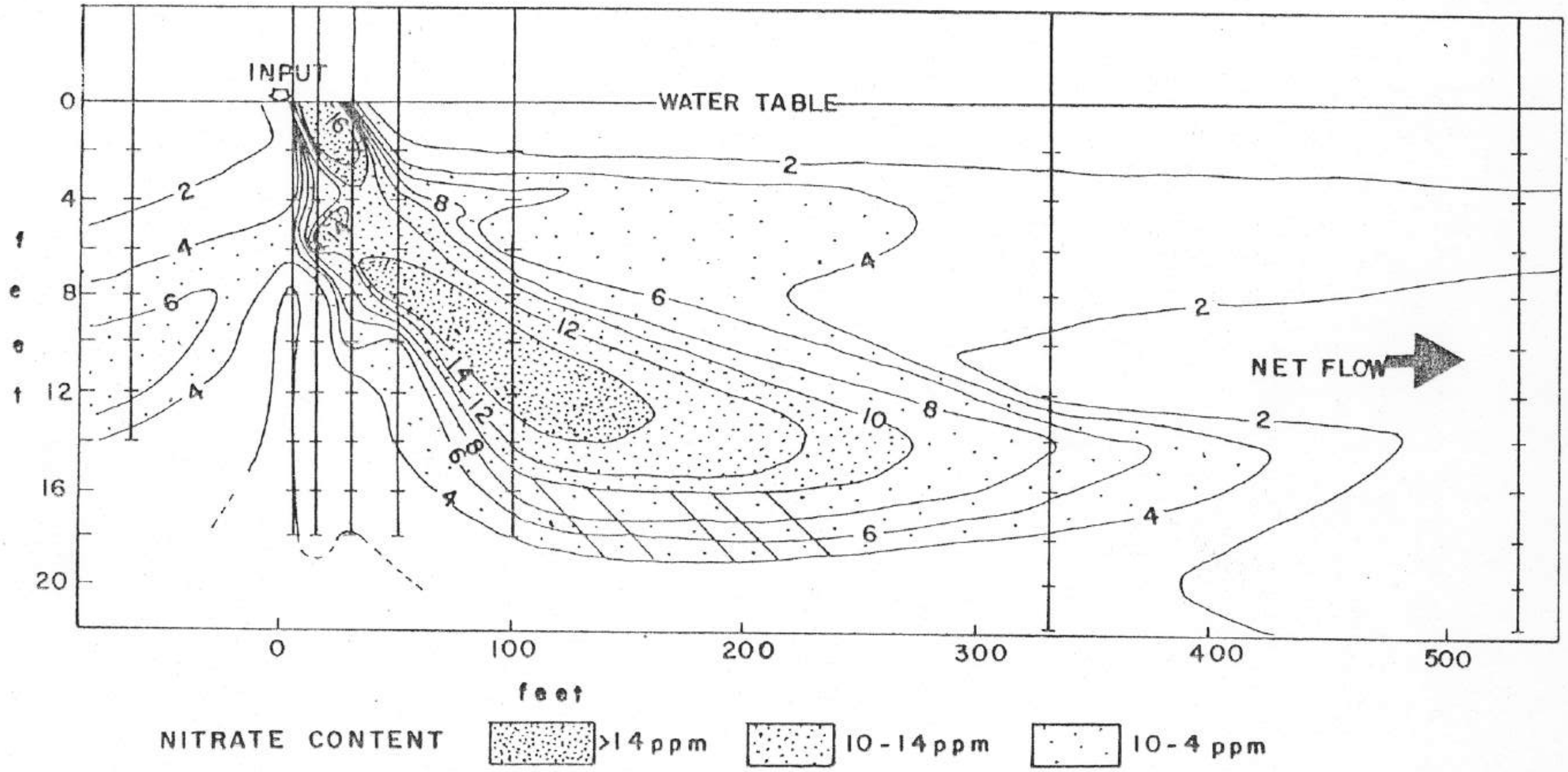


Figure 7. Cross section of a waste plume of nitrates (After Childs, et al., 1974)

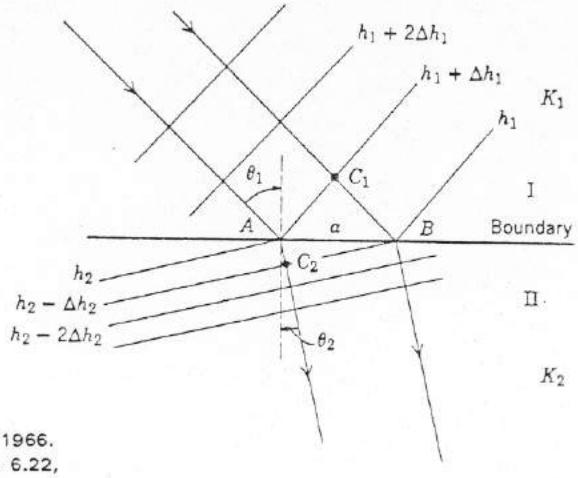


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Figure 8. Refraction of streamlines (Davis and DeWiest - 1966).

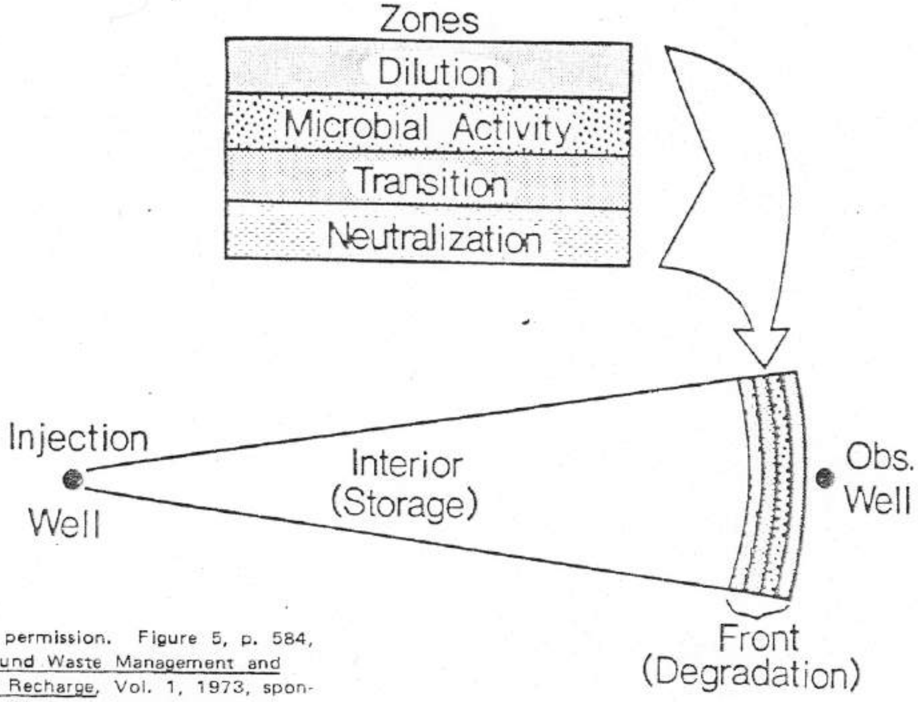

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Figure 9. Proposed geochemical model of waste after injection, into subsurface. (Leenheer and Malcolm - 1973).

The concept of dispersion of miscible fluids in porous media has received considerable attention during the past several years, especially with regard to ion exchange in soils, artificial recharge, liquid-waste disposal operations, seawater intrusion into coastal aquifers and seepage from canals and streams into and through aquifers (refs. 7, 8, 27, and 39).

Marino (ref. 37) explores the mathematical framework of simultaneous dispersion and adsorption of a solute within a homogeneous and isotropic porous media in steady, unidirectional flow fields. He concludes that in such conditions the dispersion system is considered to be adsorbing the solute at a rate proportional to its concentration. Mass transfer due to adsorption appears to play an important role in mass transport within natural flow systems.

In general, the mobility of any contaminant introduced into the groundwater system is largely dependent on the capacity of the matrix material within the porous media to adsorb the dissolved substances. However, Sigmor (ref. 42) suggests that movement into the aquifer is subject to limitations caused by degradation of the hydraulic conductivity in the porous medium. As previously mentioned, a reduction in hydraulic conductivity (or permeability) is caused by the retention in the porous media of suspended clay minerals, among other fine minerals, by means of (a) interstitial straining, (b) gravitational settling, and/or (c) adhesion and adsorption.

It is apparent that sensitive flow thresholds exist that may play some role in the chemical reactions and biological activity in an aquifer invaded by foreign materials and carrier fluids and gases. In natural, undisturbed ground-water systems, formation clogging by bacterial growth products occurs when the introduced fluid contains dissolved organic materials and bacterial growth conditions are favorable. Edwards and Monke (ref. 19) studied flow of clay suspensions (similar to some drilling fluids) through a silica porous medium and suggest that bacteria may provide a natural electrical link between the net negatively charged silica and bentonite clay particles.

REACTIONS WITHIN THE AQUIFER

The above discussion of flow through porous media has not considered the interaction between the suspended particles and substances present in solution. The chemical characteristics of ground water are strongly affected by the solids, liquids, and gases with which it has come in contact before and during the ground-water phase of the Hydrologic Cycle (ref. 3). Similarly, the composition of the mud filtrate depends upon the changes that take place as the substances added at the surface react with one another and with the cuttings derived from the formations drilled. When mud filtrate mixes with ground water, reactions may occur to form precipitates which then become subject to the filtration mechanisms listed previously. Factors of Eh and pH, as well as ionic strength, are significant in determining the extent of formation plugging and attendant mineralogical alterations (refs. 28 and 44).

Quartz is the most abundant mineral in sandstone aquifers, the most common type of aquifer. Chemical additives in the mud filtrate may react with the porous media; for example, sodium hydroxide reacts rapidly with the silica in the quartz, especially at elevated temperatures (ref. 24).

Microorganisms, such as bacteria, or enzymes produced by microorganisms, may be present in the ground water or be introduced by the drilling operation, as previously mentioned. Biological activity frequently influences chemical reactions indirectly, and vice versa, by facilitating reactions that lower or raise the pH. Redox processes also may be mediated by bacteria.

The composition, size, and activity of a bacterial population depends on many factors, including (a) temperature, (b) pH, (c) salt content, (d) concentration of nutrients available, (e) types of nutrients available, and (f) oxygen concentration (ref. 20). Because ground water normally contains little dissolved oxygen, and is generally under reducing conditions, anaerobic species are expected to predominate. Bacterial travel in confined aquifers is reportedly negligible and survival time is short. Under most conditions, the restricted travel seems to be the result of the filtering action of the porous medium rather than of "die-off" of organisms. Certain bacteria are generally considered to be responsible for the formation of hydrogen sulfide under certain conditions.

Bacteria are commonly isolated from most oil-field brines. Ground water not associated with deposits of organic matter, however, does not support extensive microbial growth. Hence bacteria carriers are presumed to be clays with associated organic materials.

There are sulphate-reducing bacteria, denitrifying bacteria, methaneproducing bacteria, plus a host of other bacteria with uncertain affinities (ref. 17). All may play roles in altering chemical equilibrium of the fluid, as well as formation cement and matrix material.

Of particular importance here is that the variety of organic compounds that can be utilized by microorganisms is almost limitless. Nearly all naturally occurring organic compounds are subject to microbial assimilation, although some, such as humic materials, are attacked very slowly.

In a study on liquid waste-aquifer interactions, Leenheer and Malcolm (ref. 35) explored several of the possible geochemical and biochemical effects of introducing an organic acid into the subsurface environment. After injection, the organic acids were first neutralized by the carbonate minerals in the aquifer. They found evidence for dissolution of the alumino silicate clay minerals by the complexing organic acids. After dilution, conditions become favorable for microbiologic degradation of the organic constituents. Methane is a proposed product with sulfate and iron reduction occurring as byproduct reactions. Figure 9 shows their proposed model of the geobiochemical cell.

Of particular importance in considering the mobility of foreign fluids in an aquifer is that most aquifers exhibit a natural, reducing subsurface geochemical environment (ref. 41). Most aquifers contain extremely low levels of dissolved oxygen. By opening the aquifer via drilling, the reduced condition is replaced by a progressively more oxidizing environment. The initial response to this change is the oxidation of pyrite, or other unoxidized minerals in equilibrium in a reduced environment, which releases ferrous, sulfide, and hydrogen ions into solution. With time, ferric hydroxide precipitates, and the ferrous ion concentration decreases. Several inorganic and microbiological agents have been observed to accelerate pyrite oxidation (ref. 45).

Within many aquifer systems, clays and shales serve as semipermeable membranes, retarding by varying degrees the passage of the dissolved elemental species with respect to water (refs. 25 and 34). The relative retardation by naturally occurring membranes of cations and anions generally present in introduced fluids has been investigated by Kharaka (ref. 33). The conclusion was reached that the retention of these ions depends on the constitution of the membrane and the specific ions involved. The retardation sequences obtained were generally as follows: $Li<Na<NH_3<K<Rb<C_s$ and $Mg<Ca<S_r<Ba$. For anions at higher temperatures the following sequence was developed: $HCO_3<I<SO_4<Cl<Br$.

CONCLUSIONS

After a contaminant enters ground water it may be immobilized by deep filtration; react chemically with components of the interstitial water; react with or be adsorbed on surfaces of the reservoir rock, or be altered through biological activity.

Under normal conditions of the porous medium, the mobility of drilling fluids in the ground-water system is clearly of very limited extent because of a variety of physical, chemical, and biological factors. The very low volume introduced into a very large volume aquifer would further minimize the impact of mobility due to a natural defense against invading carrier fluids involving (a) filtration at and near the well, (b) adsorption over the entire distance of flow, and (c) dilution, increasing away from the well or point source of entry.

It is clear therefore that improved "housekeeping" in surface operations and more effective techniques in controlling "lost circulation" will reduce the chance of point-source contamination of the local ground-water reservoir. Further research, however, is urgently needed to assess the environmental impact of "lost circulation" and related drilling and production phenomena on the ground-water system.

REFERENCES

1. American Petroleum Institute, RP13B Standard Procedure for Testing Drilling Fluids, Fifth Edition, 1974, p. 11.

2. Anon., "Drilling Fluids File," World Oil, Vol. 180, No. 2 (January 1975), pp. 37-71.

3. I. Barnes, "Water-Mineral Reactions Related to Potential Fluid-Injection Problems," in Underground Waste Management and Artificial Recharge, Vol. 1 (1973), published jointly by the AAPG, USGS, and IAHS, pp. 294-297.

4. J. Bear, Dynamics of Fluids in Porous Media, American Elsevier Pubs., New York, 1972, p. 764.

5. C. Bezemer and I. Havenaar, "Filtration Behavior of Circulating Drilling Fluids," Petrol. Trans. AIME, Vol. 237 (1966), p. 292-298.

6. D. C. Bond, "Reduction of Flow Patterns in Variable-Density Aquifers from Pressure and Water Level Observations," in *Underground Waste Management and Artificial Recharge*, Vol. 1 (1973), published jointly by the AAPG, USGS, and IAHS, pp. 357-378.

7. J. D. Bredehoeft and G. F. Pinder, "Mass Transport in Flowing Groundwater," *Water Resources Research*, Vol. 9, No. 1 (1973), p. 194-210.

8. J. D. Bredehoeft and G. F. Pinder, "Application of Transport Equations to Ground Water Systems," in *Underground Waste Management and Artificial Recharge*, Vol. 1 (1973), published jointly by the AAPG, USGS, and IAHS, pp. 191-201.

9. J. M. Bugbee, "Lost Circulation - A Major Problem in Exploration and Development," *API Drill. and Prod. Pract.*, 1953, pp. 14-27.

10. H. T. Byck, "The Effect of Formation Permeability on the Plastering Behavior of Mud Fluids," *API Drill. and Prod. Pract.*, 1940, pp. 40-42.

11. H. T. Byck, "Effect of Temperature on Plastering Properties and Viscosity of Rotary Drilling Muds," *Petrol. Trans. AIME*, Vol. 136 (1940), pp. 167-172.

12. M. D. Campbell, *Ground-Water Pollution*, (in preparation).

13. M. D. Campbell and J. H. Lehr, *Water Well Technology*; Subtitled: *Field Principles of Exploration Drilling and Development of Ground Water and Other Selected Minerals*, McGraw-Hill, New York, 1974, pp. 16-23.

14. K. E. Childs et al., "Sampling of Variable, Waste-Migration Patterns in Ground Water," *Ground Water*, Vol. 12, No. 6 (Nov.-Dec. 1974), pp. 369-377.

15. A. G. Collins, "Oil and Gas Wells - Potential Polluters of the Environment?" *J. Water Pollution Control Federation*, Vol. 43, No. 12 (December 1971), pp. 2383-2393.

16. S. N. Davis and R. J. M. DeWiest, *Hydrogeology*, John Wiley and Sons, Inc., New York, 1966, p. 197.

17. A. Ditomasso and G. H. Elkan, "Role of Bacteria in Decomposition of Injected Liquid Waste at Wilmington, North Carolina," in *Underground Waste Management and Artificial Recharge*, Vol. 1 (1973), published jointly by AAPG, USGS, and IAHS, p. 585.

18. H. G. Doll, "Filtrate Invasion in Highly Permeable Sands," *J. Petrol. Eng.*, Vol. 27, No. 1 (January 1955), pp. B53-B56.

19. D. M. Edwards and E. J. Monke, "Electrokinetic Studies of Porous Media Systems," *Am. Soc. Agr. Engineers Trans.*, Vol. 11, No. 3 (1968), pp. 412-415.

20. G. G. Ehrlich, "Role of Biota in Underground Waste Injection and Storage," in Underground Waste Management and Environmental Implications, AAPG Memoir 16, pp. 298-307.

21. C. K. Ferguson and J. A. Klotz, "Filtration From Mud During Drilling," Petrol. Trans. AIME, Vol. 201 (1954), pp. 29-42.

22. G. R. Gray, "Chemicals in Oil-Well Drilling Fluids," paper presented at 159th National Meeting, Am. Chem. Soc., abridged as "Where the Industry's Mud Money Goes," Oil and Gas J., April 1970, pp. 157-159.

23. G. R. Gray, "New Muds Designed to Improve Drilling Rate, Hole Stability," World Oil, Vol. 176, No. 6 (May 1973), pp. 84-86.

24. G. R. Gray and W. C. Kellogg, "The Wilcox Trend - A Cross Section of Typical Mud Problems," World Oil, August 1955, pp. 102-117.

25. B. B. Hanshaw, "Natural-Membrane Phenomena and Subsurface Waste Emplacement," Underground Waste Management and Environmental Implications AAPG Memoir 16 (1972), pp. 308-317.

26. J. P. Herzig, D. M. Leclerc, and P. LeGaff, "Flow of Suspensions Through Porous Media - Application to Deep Filtration," in Flow Through Porous Media, American Chemical Society, Washington, D. C., 1970, pp. 130-157.

27. J. A. Hoopes and D. R. F. Harleman, "Waste Water Recharge and Dispersion in Porous Media," Report 77, R. M. Parsons Lab. for Water Resources and Hydrodynamics, M.I.T., Cambridge, 1965, p. 166.

28. W. F. Hower, et al., "Compatibility of Injection Fluids with Reservoir Components," in Underground Waste Management and Artificial Recharge, Vol. 1 (1973), published jointly by AAPG, USGS, and IAHS, pp. 287-293.

29. G. C. Howard and P. P. Scott, Jr., "An Analysis and the Control of Lost Circulation," Petrol. Trans. AIME, Vol. 192 (1951), pp. 171-182.

30. E. E. Hulbotter and G. R. Gray, "Drilling Fluids," Encyclopedia of Chemical Technology, 2nd Ed., Vol. 7 (1965), pp. 287-307.

31. R. Kazmann, "Waste Surveillance in Subsurface Disposal Projects," Ground Water, Vol. 12, No. 6 (Nov.-Dec. 1974), pp. 418-426.

32. D. K. Keech, "Ground Water Pollution," Principles and Applications of Ground Water Hydraulic Conf., Kellogg Center, Michigan State University, December 1970, p. 20.

33. Y. K. Kharaka, "Retention of Dissolved Constitutents of Waste by Geologic Membranes," in Underground Waste Management and Artificial Recharge, Vol. 1 (1973), published jointly by AAPG, USGS, and IAHS, pp. 420-435.

34. Y. K. Kharaka and F. A. F. Berry, "The Influence of Geological Membranes on the Geochemistry of Subsurface Waters from Miocene Sediments at Kettleman North Dome in California," Water Resources Research, Vol. 10, No. 2 (April 1974), pp. 313-327.

35. J. A. Leemheer and R. L. Malcolm, "Case History of Subsurface Waste Injection of an Industrial Organic Waste," in Underground Waste Management and Artificial Recharge, Vol. 1 (1973), published jointly by AAPG, USGS, and IAHS, pp. 565-584.

36. S. W. Lohman et al., "Definitions of Selected Ground Water Terms--Revisions and Conceptual Refinements," U.S.G.S. Water-Supply Paper 1988, 1972.

37. M. A. Marino, "Distribution of Contaminants in Porous Media Flow," Water Resource Research, Vol. 10, No. 5 (October 1974), pp. 1013-1018.

38. J. U. Messenger, "How to Combat Lost Circulation," Oil and Gas J., Vol. 66, No's 20, 21 and 22 (May 1968), pp. 71-76, 90-97, and 94-98.

39. A. Ogata, "Theory of Dispersion in a Granular Medium," U.S.G.S. Prof. Paper 411-I, 1970, p. 11-134.

40. R. Palmquist and L. V. A. Sendlein, "The Configuration of Contamination Enclaves from Refuse Disposal Sites on Floodplains," Ground Water, Vol. 13, No. 2 (March-April 1975), pp. 167-181.

41. S. E. Ragone et al., "Short-term Effect of Injection of Tertiary Treated Sewage on Iron Concentration of Water in Magothy Aquifer, Bay Park, New York," in Waste Management and Artificial Recharge, Vol. I (1973), published jointly by AAPG, USGS, and IAHS, pp. 273-290.

42. D. C. Signor, "Laboratory Facility for Studies Related to Artificial Recharge," in Waste Management and Artificial Recharge, Vol. 2 (1973), published jointly by AAPG, USGS, and IAHS, pp. 799-822.

43. H. R. Sweet and R. H. Fetrow, "Ground-Water Pollution by Wood Waste Disposal," Ground Water, Vol. 13, No. 2 (March-April 1975) pp. 227-231.

44. H. S. Swolfs, "Chemical Effects of Pore Fluids on Rock Properties," in Underground Waste Management and Environmental Implications, AAPG Memoir 16, 1973, pp. 224-234.

45. F. Walsh and R. Mitchell, "A pH-Dependent Succession of Iron Bacteria," Environmental Science and Technology, Vol. 6, No. 9 (1972), pp. 809-812.

46. M. Williams and G. E. Cannon, "Evaluation of Filtration Properties of Drilling Mud," API Drill. and Prod. Pract., 1938, pp. 20-27.

47. M. Williams, "Radial Filtration of Drilling Muds," Petrol. Trans. AIME, Vol. 136 (1940), pp. 57-69.

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